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In-Situ Hydrographic Support of Naval Amphibious Operations

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Abstract

This paper discusses requirements and progress towards providing naval amphibious forces with in-situ oceanographic data collection, processing and dissemination. The generation of digital terrain models in real-time is discussed, and is shown to be a key requirement for survey automation. The utility of a GIS for tactical decision making with environmental data is presented. The functional requirements of a GIS to support this task are discussed, as well as recent efforts to utilize GIS in oceanographic data collection and analysis. Finally, data telemetry requirements are reviewed, and the results of preliminary attempts to transmit collected bathymetry data to naval vessels are given.

1. Introduction

There is an increased emphasis today (CNO, 1997) on real-time assessment of the ocean environment and the use of this knowledge to gain tactical advantage in amphibious warfare operations. To this end, the naval operational forces require the ability to: 1) conduct in-situ ocean surveys to collect needed data, 2) extract tactically relevant information from the collected data and 3) transmit the data and extracted information to the end users. Due to the dynamic temporal and spatial variations in the littoral regions of the oceans, detailed and current knowledge of the conditions at and below the surface of the water are as critical to tactical advantage as above water weather conditions. Like the weather, the littoral ocean environment does not lend itself to fine scale modeling predictions, so real-time data collection and analysis of ocean condition impact on military system performance is crucial to tactical success.

The Mapping, Charting and Geodesy Branch of the Naval Research Laboratory has been addressing many of these issues through the RMS(O) program. The RMS(O) is the oceanographic version of the Remote Minehunting System (RMS), and is an unmanned remotely-controlled semi-submersible capable of stand-off data collection operations. It is a fleet deployable system and will be capable of collecting oceanographic data including bathymetry, acoustic imagery, surface temperature and salinity, wave conditions, current profiles, sediment classification and above water wind conditions. The RMS(O) program has addressed three critical areas of the amphibious environmental data support mission: 1) survey automation for real-time data collection, 2) software requirements for rapid data processing and information extraction to support decision making and 3) transmission of data and extracted information to end users.

The next section discusses survey automation using remotely controlled or autonomous vessels. The key requirement for this effort is the real-time generation of a digital terrain model (DTM) with the collected data. The DTM's allow automation of the survey process while ensuring data quality and enable rapid human assessment of survey progress and ocean conditions. The third section discusses the functional requirements for GIS software to perform processing and analysis of oceanographic data to enable effective information extraction for tactical use. It is shown in

Section 3 that a GIS is the logical software platform for this requirement, but development beyond currently available GIS software is needed. In Section 4 transmission of the collected data and derived information is discussed. There are many possible end-users for both the data and information, and a multi-faceted approach for making these products available is required based on need and available communication bandwidths.

2. Survey Automation

Ocean surveying is a costly and typically human intensive effort. Automation of the processes involved can reduce human operator requirements, one of the most significant cost factors. Further cost-savings can be realized by performing data processing and quality analysis in real-time, enabling optimization of a survey to maximize area coverage while minimizing on-station time. Automating data processing and quality analysis is a requirement for surveying with autonomous vessels and for tactical support scenarios. For autonomous vessels there will typically be severe limitations on communication bandwidths, or no communication at all, so data processing and quality assurance must be performed on the vessel in real-time. It would clearly be unacceptable to deploy a survey system for a long duration mission without the ability to ensure the mission objectives are being met. If there is no communication channel then all decisions pertaining to mission goals must be performed by the vessel's on-board mission supervisor. Even with a communication channel, significant processing must be performed on-board to minimize communication bandwidth requirements while providing a remote human operator sufficient information to evaluate mission progress. For a tactical support scenario it is preferable to use unmanned vessels with stand-off capability for data collection since operations will likely be in a hostile environment. Often covertness is also desired, and in either case communication channels will be limited. Furthermore, in a tactical situation human resources are a premium and should not be tasked with functions that can be otherwise automated.

The NRL MC&G program has focused on automation of surveys using swath bathymetry systems. Accurate and fine-scale bathymetry remains the most significant data need in the littoral regions, and swath bathymetry systems pose some of the greatest problems in terms of data quantity and sensitivity of data quality to environmental effects. Swath bathymetry is also unique in that it is usually desired to have 100% data coverage of an area vice minimal characterization, the latter which could be accomplished employing simple gradient search techniques. Automation of swath bathymetry surveys entails consideration of two factors: data coverage and data quality. The assumed goal of the survey is to obtain 100% data coverage over the prescribed geographical area with all of the resulting processed data meeting some minimal quality constraint. In order to automate the survey process to meet this goal, data coverage and data quality must be assessed in-situ so that survey system parameters, such as navigation and sensor settings, can be altered in real-time.

The approach taken for in-situ assessment of data coverage and quality has been to generate a Digital Terrain Model (DTM) in real-time. DTM's lend themselves well to rapid machine and human visual interpretation of the processed data. Visually, a DTM readily reveals gaps in the data (holidays) and also sensor system errors which can be detected through inspection of self-consistency in the data. Generation of the DTM in real-time requires robust, fast and unsupervised algorithms that do not require human intervention or assistance. The present implementation of this system uses a custom built real-time GIS to display the processed data in the correct geographic location and a sample display is shown in Fig. 1. Tracklines, area

boundaries and other navigation information are displayed as overlays, and the vessel position is updated in real-time. The survey is executed through a series of individual lines. After each line is completed the data for that line is processed to generate a line DTM, typically requiring only a few seconds. The processing involves correcting the sonar sounding data for vessel position, heave, pitch, roll, heading, tide, sonar head depth and water column sound velocity. A gridding process is then used on the corrected sounding data to generate the DTM. Part of this process is the exclusion of data within a swath that does not meet pre-specified quality constraints, such as consistency of soundings within a grid cell. The result of this exclusion may be the appearance of gaps within the line's DTM. Once computed, the line's DTM is then displayed as a continuous color contour on the GIS. The data being collected in the current swath is displayed in real-time as individual geo-rectified soundings, which allows direct swath to swath validation of system operation – if the overlapping colors do not match at the same geographic location then an error exists. The resulting display is very nearly a final product. Post analysis processing could include corrections for tides, detailed inspection of data outliers and generation of a DTM using the entire data set vice line by line.

Generation of a real-time DTM from swath bathymetry data has a profound effect on survey efficiency and data quality. The DTM readily reveals gaps in the data due to poor quality data (excluded in the processing) or misalignment of adjacent swaths. It also allows intra-swath and inter-swath data consistency checks, which enable immediate detection of sensor system problems. Most importantly, it allows assessment of actual vice predicted sensor system performance. The DTM is much smaller in size than original data and lends itself well to transmission over narrow bandwidth communication channels.

Once generation of the DTM is accomplished it is possible to automate the survey system while ensuring data coverage and data quality goals are met. The RMS(O) prototype, the ORCA, is presently capable of fully automated 'hands-off' surveying using the real-time DTM to assess survey performance. With this system, the operator specifies a region to be surveyed using the GIS and starts the survey vessel along one side of the polygon that bounds the specified area. The automated system then pilots the survey vessel along the first line. After the first line is completed, and while the vessel is turning, the processing system determines the next line's waypoints based on analysis of the last swath's DTM. The processing of the previous swath's DTM evaluates environmental and sensor system performance impacts on the quality of the collected data and adaptively determines where the next survey line should be placed. The waypoints for this line are automatically passed to the autopilot, and all subsequent lines are handled in this manner.

3. GIS Requirements

The need for GIS capabilities in ocean exploration, surveying and resource exploitation has been well recognized in the literature. However, actual implementation is progressing slowly, primarily due to the typically large data quantities in oceanographic data sets (bathymetry in particular) but also due the to difficulty of GIS use and integration in the field with the types of data collection systems encountered. A recent paper by Wright and Goodchild (1997) directly addressed application of GIS to the oceans, and indicated the difficulties involved with today's technology in using GIS to effectively manage ocean data. In this paper they state one of the key benefits: "the ability provided by GIS to synergize different types of data collected from multiple sampling platforms has provided... more information and insight than could be obtained by considering

each type of data separately." However, they also indicated that commercial GIS's still do not provide the functionality required for the input and processing of spatial oceanographic data. They cite areas of needed improvement including: a need for measurement-based vice coordinate based spatial data structures due to the nature of ocean data --- boundaries are fuzzy, locations change, merging of measurements from different sources; data may be sparse in one or two dimensions, indicating the need for adequate interpolation methods; data is large in size.

Hatcher (1997) discusses a recent effort at MBARI (Monterey Bay Aquarium Research Institute) to use ArcView for real-time oceanographic data collection support. They clearly state the need for GIS support at sea: "an oceanographic cruise is very costly, involves data from many different sources, is a long time in planning, and often takes place in remote locations not frequently visited... GIS has proven itself as a valuable tool for oceanographic cruise planning and data analysis." In this paper they described their customization of ArcView to incorporate real-time oceanographic data including position and still image captures. Bathymetry and acoustic backscatter data were collected but they indicated that its use was arduous due to the large volume and extensive processing required. Their description of the implementation also indicates that bringing the different sources of data into the GIS was awkward.

Li (1995) also addresses the difficulty in using bathymetric data with a GIS: data sets are large, data is obtained at multiple resolutions, and it is hard to associate attributes since there are no clear boundaries separating features. Bathymetry data is typically available in digital forms such as irregularly distributed discrete points, grids, and triangulated networks (TIN's) which are treated as digital terrain models (DTM's). Li indicates that an object-oriented approach is required, one that organizes data by topographic features. Wentzell (1995) describes the benefits of integrating hydrographic information systems (HIS) with GIS. He points out that there are several categories of users of marine information: nautical officers and vessel pilots who require information dynamically, static users involved with investigation, planning and management, and those involved with the acquisition and supply of the data. ECDIS is an example of a GIS-like system that has been tailored specifically for the use of vessel piloting. Each of these applications require usage of the same data, but each manipulates it in different ways; the flexibility offered by a GIS could be used to tailor the data to all of these specific needs, vice developing independent software platforms to support each.

Max (1997) discusses the requirement for hydrographic data in military operations where fast turn-around data collection and dissemination are vital. He indicates a clear need for GIS, but with proper integration into related systems. He describes Rapid Environmental Assessment (REA) which requires in-theatre acquisition of relevant data, rapid data fusion that extracts only the military relevant information for any set of requirements, and archives and optimizes them in such a way that they can be used with relative ease by the user. Simplicity of data fusion is necessary for speed, but maximum flexibility in the way the data may be fused is required to support a variety of particular operational needs. Referring to the ability to overlay/superimpose different layers of data for making go/no-go decisions, he states: "This selective edition is a feature of GIS and is one of the main reasons why a user front-end to an environmental information system should be GIS based, rather than being resident in single file-images or gridded databases."

A key difficulty in using a GIS for bathymetry data processing lies in the extreme size of the data sets, particularly for modern wide-swath multibeam systems. A more fundamental issue,

however, is that swath bathymetry data is more like raster than vector data in its nature and GIS systems have traditionally been vector based. Bathymetry is a sampled continuous process (Li 1995, Hinton 1996) and different resolutions of the data require resampling (a gridding process); in contrast, vector data is typically scale independent. Bathymetry data is also non-uniformly sampled in space due to the data collection process, so the very first processing step, which may include rejection of poor quality data, is gridding into uniform cells. To regrid the data, neighborhood data operations are required. There is no equivalent to this operation in vector data processing (Faust 1991) but it is standard in raster processing systems. Bathymetry also has a much higher entropy (Wilkinson 1996) than typical vector data, as it is a sampled field vice an object (Ehlers 1989, Li 1995). It is the raw data from which objects, such as polygons, contour lines and selected soundings, would be extracted after analysis. Also, the data quantities are too large to handle with typical vector GIS systems (Li 1995). Conceptually, each sounding could be handled in a vector system as a point (with its associated attributes), just as each pixel in a remotely sensed image could be. But in both cases this is not a 'natural' approach for this type of data, and the data quantities rapidly exceed the capabilities of vector GIS systems.

It is evident from the previous discussion that the features of a vector based GIS system are desired, but that raster processing capabilities are required to be able to effectively handle oceanographic data, particularly bathymetry. Desired features of common vector GIS systems include a common database, cartographic capabilities, and the ability to select and categorize objects based on a user-specified set of attributes. The key features of raster processing systems that are not included in vector GIS's are the ability to handle (store and process) large data quantities and to perform neighborhood operations. Faust (1991) provides a categorization of the functional characteristics of a conceptual integrated vector/raster GIS system. He contrasts raster and vector systems: raster GIS systems use multiple variables that are normally coded into cell or raster grids, and data analysis occurs in the raster domain; vector systems capture data in vector format and analyze in vector domain: polygons, lines, points, arcs and nodes. He lists the functions of an integrated GIS as follows:

- Information Display. Vector data must be converted on the fly into raster.
- Attribute handling. One of the basic GIS functions is the ability to display GIS data that satisfies a user selectable set of attributes.
- Vertical Analysis. Used in raster based systems, this includes algebraic or logical combination of layers - multi-spectral processing for example. This feature could be used to analyze correlations between different forms of oceanographic data.
- Proximity Analysis. An example of this function would be defining all geographic regions that lie within a certain distance of defined objects. This could be used with hydrographic data to indicate exclusion zones for hazardous conditions such as shoals or for pipelines and cables near anchorage areas. This is a common feature in vector systems.
- Neighborhood operations. For bathymetric data this type of operation is required to perform data gridding, generate selected soundings, and do region growing for tasks such as seafloor acoustic or sediment classification. No clear equivalent exists in vector analysis; most vector analyses involve Boolean operations on attribute data.
- Time-based operations. This is the ability to observe the change in a measured feature with time. Examples for hydrographic data would include the analysis of the shape of sediment plumes from rivers or the effect of storms on ship channel sedimentation.

- Vector-Raster conversion. Conversion of vector data to raster form could also be utilized to combine vector data with raster data for vertical analyses or time-based analyses.
- Raster-Vector conversion. This is typically an operator intensive task and normally an extremely difficult process. Seafloor classification into polygons of uniform type and the generation of selected bathymetry soundings or contours from raw sounding data are examples.

Hinton (1996) also details well the benefits of a combined capability of vector and raster processing: a combined suite for image processing, database, cartography, and GIS. Among the new capabilities introduced are vector data constrained classifications of raster data, and updating of vector data with raster data.

In his review paper, Ehlers (1989) investigated the integration of GIS and remote sensing capabilities and illustrated the fundamental differences between the two forms of processing. He indicated that GIS systems were originally developed to allow combination of attribute information about land with its cartographic representation, which is needed to perform spatial analyses; GIS's tend to rely on fairly uniform and predetermined data. He states a key concept: that cartographic data is obtained by abstracting some information about the world and discarding the rest; image (raster) data is a lower form of information where the interpretation remains to be done. Image interpretation in remote sensing is that area which seeks to abstract the higher-level information from images. Wilkinson (1996) reiterates this concept stating that this process reduces the image entropy allowing for lower storage requirements, and is more easily understood by the user in cartographic terms. He also indicates that this process is extremely difficult, and that image segmentation has taxed the best minds of the remote sensing community for two decades. Ehlers (1989) also contrasts cartographic and remote sensed data on a conceptual level: the former is object based and usually fills an empty two-dimensional space with objects; the latter is field based and separates non-empty space into a tiling of raster elements (pixels). Raster-vector integration in GIS has been an active research issue for over a decade, with remote sensing applications providing the major requirements for this capability.

Ehlers (1989) indicates that the "raster/vector dichotomy" has eluded many attempts at integration. Raster processing hardware and software have evolved largely within the field of remote sensing, and for the most part this advancement has been separate from GIS development. The driving factor behind the separate remote sensing development has been processing power - "the CPU processing burden for image analysis is sufficiently high that raster data structures are the only reasonable choice..." (Ehlers 1989). Ehlers states that if GIS technology is to be used for Remote Sensing applications that it "must be adapted, modified and extended". With respect to the ability to integrate GIS with other systems, Abel (1992) states that: "Some systems provide rudimentary programming tools, but GIS's are often so complex structurally that programming additions are extremely difficult and time consuming." He indicates that GIS's require fundamental extensions to achieve effective integration. But as the research efforts have born out, integration of remote sensing and GIS functionality is not a straightforward issue. Ehlers (1989) indicates this clearly in the following statement: "The integration of remotely sensed data requires that the GIS be based on deeper, more complete models of territory. The fact that most GIS today are based on a more superficial model is indeed one of the major stumbling blocks to improved integration."

In a recent review paper, Hinton (1996) observed a "...historical move towards closer integration of remote sensing and GIS technologies and the requirements of integrated software systems to enable remotely-sensed data to be combined with vector datasets for maximum effect. But he adds that "most, although not all, GIS's available are based on a vector data model. While many now incorporate the facilities to store and display raster data they do not include image processing functionality." Both Hinton (1996) and Burrough (1986) state that more image processing capabilities are needed in GIS's since environmental parameters are generally continuous (i.e. raster form) and remotely sensed images are readily available forms of spatially referenced geographical information. Hinton (1996) describes the ultimate goal for an integrated GIS as a system that does not rely on data conversion and provides transparent data flow between the images and the vector database. However, Wilkinson (1996) points out that "There is still little consensus over what kinds of data structures to use or how to manage error and uncertainty."

An integrated raster/vector GIS is the natural platform for hydrographic data processing, product generation and data analysis. The requirement for an integrated GIS system is clearly stated by Max (1997), where survey operations need a rapid turn-around of the collected data - such as in support of military operations. Furthermore, GIS offers a query based user interface that would enable the collected data to be used for bounding environmental parameters and displaying zones with acceptable conditions for deployment of vessels, sensors and weapon systems. Hatcher (1997) also makes this statement in regard to oceanographic research missions. His paper indicates some integration of GIS into the real-time data collection process, but also clearly demonstrated the inadequacies (in terms of ease of use) of a standard vector GIS system. It is evident from the recent literature (Hinton 1996, Ehlers 1989, Faust 1991, Wilkinson 1996) that development remains to be done in order to create a fully integrated raster/vector GIS system. It is also indicated (Wright 1997, Li 1995) that an object-oriented system provides the natural approach to handling hydrographic data. While the industry has made progress towards integrated vector/raster functionality in GIS, it is apparent that significant work remains to be done.

4. Data Transmission

Historically, and for the foreseeable future, data collection capabilities outpace communication technology. Line of sight communication systems are reaching beyond the megabit range, and ship-to-satellite links (uplink) are approaching data rates in the hundreds of kilobits. However, modern swath bathymetry systems can readily generate gigabytes of data in a one-day survey. In military tactical operations dedicated high bandwidth communication channels are a premium asset and must be allocated based on immediate priorities – which will likely not include transmission of raw survey data. Consequently, earnest consideration must be given to who the users of the data are, and for each user the specific needs must be identified in terms of the type of data/information transmitted, its associated size and operational priority.

For bathymetric data there are many end-users, with varied requirements for the quantity of data and the level of processing. Groups involved in chart making and data base updates will likely require the full `raw' data set, as in-situ processing does not typically provide sufficiently detailed discrimination of the data for their use. Groups concerned with using bathymetry in ocean prediction models (current, tides, etc.) will likely want processed data, but at the highest resolution possible. Both of the aforementioned groups are typically shore-based, requiring

significant human and computing resources. These efforts also require considerable time, so little is gained by using wireless telemetry assets for these large datasets. It is more practical in these cases to physically transport the data to a facility with landlines, and then post the data at a computer site that allows direct download by the users as it becomes available.

Tactical uses of bathymetry include a wide variety of processing levels and data size requirements. Safe navigation of vessels requires only the location of navigation hazards and shallow areas. Extensive processing is required on the original data to extract this information, but the resulting data size is quite small. For use in sensor/weapon performance models or for terrain based guidance a DTM is generally required, which also requires significant processing but has a moderate data size. In this discussion it is assumed that the survey data is collected during or directly preceding a tactical operation, so the full quantity raw data must be passed from the sensor system to the processing system that will generate DTM's and other required data products.

Presently, the ORCA system utilizes a 1-Mbit/sec line of sight radio link for transmission of the raw bathymetry sensor data to the ORCA's host ship. The data being sent are the individual soundings from the Simrad EM950 sonar, which corrects for heading, heave, pitch, roll, vessel depth, position and sound velocity in the ORCA. The bandwidth requirement for this data is approximately 150-Kbits/sec. This data is processed in real-time on the host ship to produce a DTM that is monitored by human operators to ensure proper survey progress, and by the autonomous survey system that analyzes the data and directs vessel navigation. Since the RMS(O) will have an over-the-horizon autonomous mode of operation, it is planned to transition the DTM generation and autonomous survey system from the host ship onto the survey vessel; logging of the raw data will be performed on the survey vessel, and this data will be retrieved when the vessel is retrieved by the host ship. Adequate processing power is already available in the RMS(O) sensor package to perform these new processing functions on-board, and it is anticipated that transmission of the resulting DTM will require only 2-10Kbits/sec. It is desired that the generated bathymetry DTM's, and other processed oceanographic data, would be passed directly to the on-scene command ship in a tactical operation. The Meteorological Officer typically resides on the command ship and provides weather assessment for the entire battle group. Likewise, it would be logical to have the oceanographic data sent to a centralized facility that would further processes and analyze the data and disseminate only the required information (such as the location of navigation hazards) to the other vessels. The actual collected data and the DTM is not needed beyond this point.

Experiments have been performed in which the DTM's have been transmitted to naval vessels, as a first effort in determining how to transfer data from the survey vessel to a user at sea. Three approaches were attempted with the USS John L. Hall (FFG-32), which has a minimal communication suite. While DTM's involve much less data than the raw soundings, a DTM of a nominal area is still fairly large. For example, a 2 square mile DTM of the Pensacola Bay, Florida area (1m contour, 1:5000 scale) is approximately 3 megabytes. Three transmission approaches were attempted with the USS Hall: Inmarsat, standard navy messages, and JMCIS (Joint Maritime Command Information Systems). Passing data via standard navy messages and JMCIS was successful but awkward and required significant human interaction. Message size restrictions in both instances required segmentation at the sending end and reconnection of the pieces at the receiving end. The Inmarsat data transfer allowed the entire file to be transferred at once, but required significant effort since this communication channel was designed such that the ship is the originator of calls and the connection had to be manually initiated.

In the last few years, the U.S. Navy has moved towards a 'push-pull' communications concept where small quantities of data are 'pushed' to many users (such as operational orders) but large quantities of data are made available to be 'pulled' by the few users that require it. This approach allows the user to decide how best to allocate their limited communication channels to best meet their immediate goals. A test was performed with the USS Essex (LHD-2) using this approach. A DTM was posted on an U.S. Navy network web site at a shore facility and was easily downloaded by the ship while it was in port. Conceptually, the vessel tasked with performing oceanographic surveys would process the collected data on-board, generate DTM's and extract information for known requirements, and then use a satellite up-link or local battle group network to post the results on a tactical web site.

5. Summary

This paper addresses some of the data processing and data transmission requirements for in-situ oceanographic data collection and utilization in support of naval amphibious operations. In-situ data collection is required since it is not practical to survey all the tactical areas of interest, it is difficult to predict where data may be needed, the environment in the littoral regions changes significantly with time, and fine scale local phenomena cannot be adequately predicted with models. Real-time generation of DTM's by the survey system was discussed, and it was shown how this enables autonomous surveys to be conducted while ensuring data coverage and data quality requirements are met. It is stated that a GIS is the logical platform with which to analyze environmental data for making tactical decisions. GIS offers a query based approach to data analysis, which lends itself readily to determining go/no-go conditions for military sensors, weapons and vessels. The functional requirements for such a GIS are discussed, and it is noted that further development remains before commercial systems can meet these requirements. Data telemetry was briefly addressed, and initial test results were discussed. Bathymetry data was telemetered to naval vessels and it was observed that using a pull method was the most effective for transferring DTM's. To reduce communication bandwidth requirements, the collected data should be processed as close to the source as possible and where practical information, not data, should be sent to the user.

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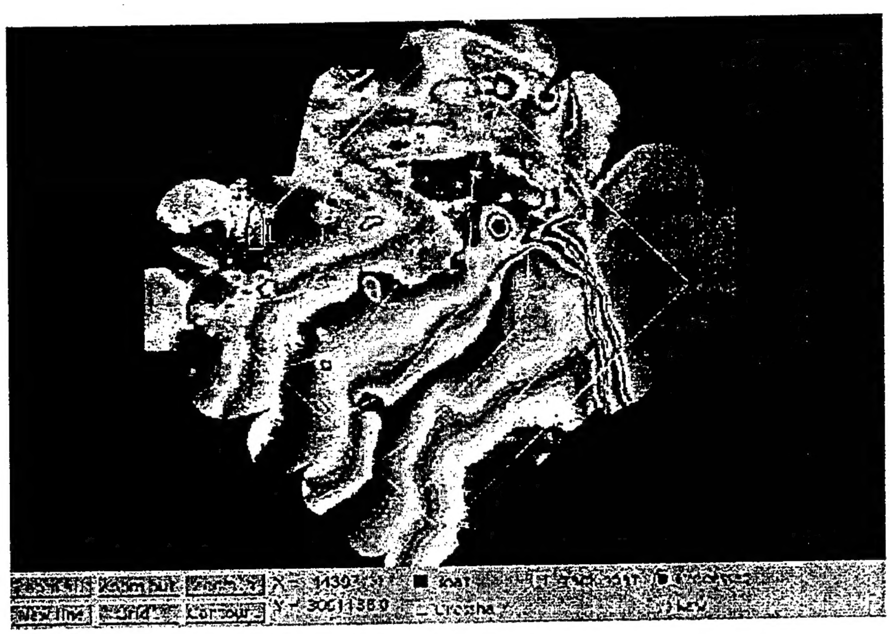

Figure 1 Real-Time Bathymetry DTM Display